REFERENCES.

(1) 'Roy. Soc. Proc.,' A, vol. 99, p. 336 (1921).
(2) Bragg, 'Phys. Soc. Proc.,' vol. 34, p. 33 (1921).
(3) Labrouste, 'Ann. de Phys.,' vol. 14, p. 164 (1920).
(4) 'Nature,' vol. 107, p. 522 (1921).
(5) Langmuir, 'Journ. Amer. Chem. Soc.,' vol. 39, p. 1868 (1917).
(6) Lewkowitsch, 'Oils, Fats, and Waxes,' 5th edit. (1914).
(7) Krafft, 'Ber. Deut. Chem. Ges.,' vol. 22, p. 812 (1889).
(8) Jeffreys, 'Amer. Chem. Journ.,' vol. 22, p. 30 (1899).
(9) Stephenson, 'Biochem. Journ.,' vol. 7, p. 431 (1913).

The Corrosion of Iron and Steel.

By Sir Robert Hadfield, Bt., F.R.S.

(Received May 25, 1922.)

Introduction.

The subject of the corrosion of iron and steel is a most important one, yet with the exception of a minor contribution by Dr. E. Newbery and the author in 1916, no communication has been presented to the Royal Society for the last one hundred years. This paper refers to the wastage of the world's iron and steel due to corrosion, and describes a number of recent experiments carried out by the author with regard to copper-steel. It is hoped that these results will add to the general knowledge on this subject of corrosion from both the scientific and practical point of view.

Careful estimates appear to show that there is a present annual loss of over 40 million tons of iron and steel under corrosion and consequent removal of material rendered unserviceable. Taking into account the cost of protecting the material, the author estimates that the aggregate annual loss due to the effects of corrosion is probably well over 500 million pounds sterling, based on prices which have prevailed during the last few years.

The introduction of alloy steels which possess high capacity for resisting corrosion should be encouraged, and although higher in the first cost they will probably be found more economical in the long run.

The great importance of economy in the use of iron, and of studying methods to avoid or reduce rusting or oxidation, is shown by valuable and interesting statements in a recent article, 'Iron Ore in Europe,' by Prof. J. W. Gregory, one of our Fellows. In reviewing a report by Mr. Max Roesler, of the U.S.

Geological Survey, on the iron ore resources of Europe, Prof. Gregory says it appears from this statement that the reserves of iron ore in the world are estimated only to be sufficient to maintain the same rate of production as in 1913 for 1000 years. On the other hand, if the output of iron should increase, as is quite possible, in fact probable, in the same ratio as the pre-war rate of even only 5 per cent. per annum, then the world's supplies will be exhausted in about 150 years. A serious statement indeed!

Last year the total production of pig iron, which is the basis of practically all iron and steel, was only 35 million tons as against the pre-war maximum of 78 million tons, but this reduction can only be a temporary one. For example, supposing the Chinese commenced to use iron and steel on a large scale, the demand on the iron ore supplies of the world would be very great, as the present output of pig iron would soon be doubled. Dr. J. S. Unger, Research Engineer of the Carnegie Steel Company, states that if this country, China, used steel in the same quantity *per capita* as the inhabitants of the United States, half a million tons of steel would be consumed every 24 hours.

It may be interesting to add, as showing the enormous output in the United States—and that their use of the metal iron is not likely to decrease, but will surely increase—each blast furnace there has an average output of 120,000 tons per annum, Germany 55,000 tons, and England 28,000 tons.

In 1913 each person in the United States used 700 lb. of iron, and in 1917 the production *per capita* was nearly half a ton. A similar use in this country would mean that we should have to produce about 23 million tons of pig iron, and even at the American rate of output for 1913, our production would have to be 14 million tons. As a matter of fact, the maximum output in Great Britain has not yet reached 11 million tons.

Whilst Prof. Gregory's estimate is necessarily to some extent speculative, yet such a statement from an authority on the subject shows how great is the importance of studying this question of corrosion more closely than has been done in the past, in order to lead to economies being effected.

Dealing first with the work of the Institution of Civil Engineers, by the kind permission of the Corrosion Committee of the Council of that body, the author is able to explain the research work now in hand and its objects. An interim report on the progress of the research will shortly be published by the Committee, and will show the work completed up to the present time. The work was commenced by the formation, in 1916, of a special Committee, under the able guidance of its Chairman, the late Sir William Matthews, K.C.M.G., to deal with problems with regard to the deterioration of structures exposed to sea action. Its present Chairman is Mr. Maurice Wilson, M.Inst.C.E. Encouragement in funds has been provided in a generous manner by the Department of Scientific and Industrial Research, who recognise the great value of the investigations. The total grants from this source have amounted to several thousand pounds.

Description of the Ferrous Materials Employed in the Research.

The specimens prepared by the author are represented by 14 types of ferrous material, in all 1,330 specimens, of which 955 have already been allocated by the Committee for the Sea-Water Corrosion Tests, also those required for mechanical, microscopical, and other laboratory tests.

The materials, classified into four main sections, are indicated in Table I, together with a very complete analytical record of their chemical composition.

The wrought iron, Section I, was furnished by the Low Moor Iron Company, and the "Armco" iron by the Shelton Steel and Iron Company. The carbon steels and special steels, Sections II and III, were produced under specification fixed by the author, and were made by Hadfield's, Limited, of Sheffield, while the cast iron, under Section IV, was supplied by the Lilleshall Company.

The specimens in all cases, excepting naturally the cast irons, are prepared from rolled bars 3 inches in breadth by ½ inch in thickness, the length of each specimen being 24 inches. In order to carry out the tests under conditions as nearly as possible resembling those met with in constructive work, the specimens are prepared in the condition "as rolled" without further heat treatment, being allowed to retain the oxide skin produced in rolling (in the case of the cast irons the casting skin). There is, however, a small number of specimens included experimentally from which the skin had been removed by grinding.

In view of the importance of the subject some of our Fellows might like to have test pieces of the author's own specimens, prepared over many years, with which to experiment, that is, ordinary and alloy steels of a large variety of types. If so, the author will willingly place, without cost, sets of these specimens at the disposal of those Fellows interested.

The tests included complete analytical tests, including the percentage determination of carbon, silicon, sulphur, phosphorus, and manganese, and in the special steels, also nickel and chromium; also mechanical tests, comprising tensile, shock, and hardness tests. In addition, the micro-structure of all the materials has been examined and photographed in view of its important bearing on corrosion.

The total number of individual tests made is 203, made up as follows:—
26 tensile tests, 104 Fremont shock tests, 26 Izod shock tests, 26 micro-test pieces, 21 test pieces for laboratory corrosion tests. 78 Brinell-Ball hardness tests were also made.

The specimens have been despatched to testing stations at Auckland, Colombo, and Halifax (Canada), also to Plymouth. They are made up in various forms, and the points under investigation cover:—The effects of total and intermittent ("half tide") immersion and exposure to marine atmosphere; also corrosion in fresh water. Variations in corrosion arising from geographical situation. The influence of strain in the metal, and of surface scale arising from the manufacturing operations; also of certain structural details, that is, items such as bolts and rivets, and the contact of dissimilar metals. The mechanical properties of the corroded materials will also be investigated.

The particulars given will, the author hopes, give a sufficient outline of the scope and bearings of this important research. The work of the Committee in planning the details has required very careful thought, and the preparation and arrangement of such a large number and variety of specimens has been no easy task, great care, in particular, being necessary to avoid the possibility of mixing, which might easily occur in 1500 specimens of so many types of material.

The Resistance to Corrosion of Steel containing Copper.

It has been stated in America that mild steel containing a small percentage of copper has proved superior in resisting corrosion, as compared with ordinary mild steel. Such a ready and inexpensive means of mitigating the evils of corrosion is naturally attractive, specially as mild steel forms the great bulk of the world's structural steel. The author has therefore been led to make a particular study of these claims.

The American tests of the copper steel, which formed part of an extensive research with a variety of materials and conditions of exposure, were carried out by the Committee of the American Society for Testing Materials. The results are published in a Report of the Committee, dated 1920, and in a number of papers* by Mr. D. M. Buck, Metallurgical Engineer to the American Sheet and Tinplate Company, Pittsburg. For the precise

---

* 'Research on the Corrosion Resistance of Copper Steel'; 'Recent Progress in Corrosion Research'; 'Copper in Steel—The Influence of Corrosion'; 'Copper in Steel Tie Plates'; 'Influence of a very Low Percentage of Copper in Retarding Corrosion'; A Review of the Development of Copper Steel.'

Table I.—Description of the Materials used in this Research, and their Analysis.

Type of material.	Classification letter.	Analysis.								Treatment.*
		C.	Si.	S.	P.	Mn.	Cr.	Ni.	Cu.	
Section I.—Irons (Rolled and Forged).										
Wrought iron	N.	0·02	0·14	0·013	0·113	Tr.		No. 1 bar		970° water.
		0·01	0·15	0·012	0·114	0·03		No. 2 bar		560 ,,
Swedish charcoal iron	P.	0·02	0·03	0·019	0·022	0·01	—	—	—	970 ,,
		0·04	—	—	—	0·03	—	—	—	560 ,,
" Armco " iron	M.	0·03	0·03	0·032	0·016	0·06		No. 1 bar		970 ,,
		0·04	0·04	0·033	0·019	0·07		No. 2 bar		560 ,,
Section II.—Carbon Steels.										
Mild steel with low Mn. and high S. and P.	B.	0·21	0·17	0·090	0·060	0·33	—	—	—	900° water.
		0·22	—	0·115	0·073	0·35	—	—	—	650 ,,
Mild steel with 0·7 per cent. Mn.......	F.	0·23	0·16	0·061	0·048	0·68	—	—	—	900 ,,
		0·25	—	0·064	—	—	—	—	—	700 ,,
Medium carbon steel with low S. and P.	E.	0·34	0·20	0·024	0·027	0·71	—	—	—	900 ,,
		0·35	—	0·026	—	0·72	—	—	—	650 ,,
0·40 per cent. carbon steel	D.	0·40	0·20	0·049	0·045	0·85	—	—	—	900 ,,
										650 ,,
Section III.—Special Steels.										
Mild steel plus ½ per cent. copper	G.	0·21	0·14	0·043	0·046	0·94	—	—	0·63	850° water.
		—	—	—	—	0·95	—	—	0·64	650 ,,
Mild steel plus 2 per cent. copper	H.	0·22	0·14	0·033	0·041	0·90	—	—	2·18	850 ,,
		0·23	—	0·035	0·043	0·92	—	—	2·19	700 ,,
3½ per cent. nickel steel	K.	0·31	0·18	0·029	0·038	0·54	—	3·75	—	850 oil.
										650 water.
36 per cent. nickel steel	L.	0·09	0·09	—	—	0·77	—	36·43	—	
		0·15	—	—	—	0·97	—	36·67	—	940 ,,
Non-rusting steel	J.	0·36	0·22	—	—	0·13	13·57	—	—	875 ,,
										750 ,,

Section IV.—Cast Irons.

Hot blast cast iron	Q.	*a*1·88 *b*1 07 *c*2·95	2·16	0·105	0·856	0·28	No. 1 bar	Not heat treated.
		*a*1·84 *b*0·94 *c*2·78	2·52	0·103	0·84	0·26	No. 2 bar	
Cold blast cast iron	R.	*a*2·75 *b*0·72 *c*3·47	1·66	0·067	0·455	0·74	No. 1 bar	Not heat treated.
		*a*2·55 *b*0·80 *c*3·35	1·77	0·066	0·50	0·73	No. 2 bar	

a = graphitic carbon. *b* = combined carbon. *c* = total carbon.

---

* Under this column is given the heat treatment to which one specimen of each material was submitted for the purpose of mechanical test, that is in addition to the test carried out representing its condition as submitted to corrosion. "970° water and 560° water" means, for example, that the specimen was at about 20° C., afterwards heated to a temperature of 560° C., and quenched again.

behaviour of the copper steel, under various conditions of exposure, these papers should be referred to.

Experiments* on copper steels made by Prof. O. Bauer, of Berlin, have shown that under most conditions the influence of copper is uncertain, and only in the sulphurous atmosphere of manufacturing districts has the copper any perceptible restraining influence against corrosion—the latter fact is rather confirmed by laboratory tests. As a general conclusion, it is considered that the addition of copper for the purpose of preventing or mitigating corrosion, would not be generally advisable. Copper is most beneficial in those steels relatively high in phosphorus content, and the results therefore in this respect differ from those of Mr. Buck quoted above, in which the *rôle* of copper is believed to be that of neutralising the harmful effects of sulphur.

The amount of copper in the specimens investigated ranged from 0·1 to 0·4 per cent., and in the author's opinion the value of the research would have been enhanced had some specimens free from copper been included for comparison.

In a preliminary examination of the question the author made the following tests. Two clean and polished specimens, one (No. 2824) of mild steel containing 0·16 per cent. of copper, and another (No. 2825) of wrought iron, were completely immersed in artificial sea water for 48 hours at 80° F., with results as follows. (The loss of weight, following the usual practice in the Hadfield Research Laboratory, was determined after removing loose corrosion products by rubbing the specimens with hard soap. Such treatment it has been found does not remove any appreciable amount of uncorroded steel.)

Specimen No.	Material.	Analysis.						Size of specimens.	Loss in mgrm. per sq. cm. exposed to corroding action.
		C.	Si.	S.	P.	Mn.	Cu.		
		p.c.	p.c.	p.c.	p.c.	p.c.	p.c.	cm.	
2824	Steel containing Cu	0·20	0·01	0·078	0·043	0·50	0·16	12·5 × 2·5 × 0·25	4·2
2825	Wrought iron	0·11	0·01	0·073	0·345	0·47	0·02	12·5 × 2·5 × 0·25	3·2

Under these conditions, therefore, the results show that steel containing 0·16 per cent. of copper is less resistant than wrought iron.

Later the author was kindly favoured by Mr. D. M. Buck with specimens of the American copper steels, in the form of pieces from rolled sheets suitable for corrosion experiments, together with similar specimens from the same heat of open-hearth steel to which copper had not been added. Mr. Buck's analyses of the two materials are as follows:—

---

* 'Stahl und Eisen,' vol. 34, pp. 37–45, January 13, 1921; also pp. 76–83, January 20, 1921.

	C.	Si.	S.	P.	Mn.	Cu.
5127 A......	0·12	0·008	0·037	0·023	0·53	0·268
5127 B......	0·14	0·007	0·038	0·023	0·53	0·018

With these specimens a number of corrosion tests have been carried out by the author under the varying conditions indicated in Table II. In every case the specimens were tested in pairs, that is one specimen of the steel (A) containing copper and another of the steel (B) free from copper exposed simultaneously. All conditions as regards manipulation and exposure were identical for the two materials.

The specimens were received from Mr. Buck covered with their oxide scale produced by the rolling process, and as this represents the condition under which such material would in general be used, the exposure tests in the atmosphere and in artificial sea-water were carried out with this skin intact. Duplicate specimens were, however, prepared and exposed simultaneously, from which the skin had been removed, the surface then being polished until free from visible scratches.

Atmospheric corrosion was observed both in the pure country air at Hathersage, 11 miles from Sheffield, and also simultaneously in the rather sulphurous atmosphere of the manufacturing district of Attercliffe, Sheffield, where the Hecla Works are situated. This exposure took place, as it happened, during the exceptionally dry period of the summer of 1921.

The remaining tests have been carried out under laboratory conditions. In these the specimens were immersed for a period of 21 days, cleaned and weighed and the loss recorded. In this condition without further preparation they were re-immersed for a period of three months.

For the short-period tests—7 days—shown in Table II, specimens were used which had already been tested in other ways. The effects of the previous test, however, had in these cases been obliterated by removing the surface to a sufficient depth and repolishing.

From these results the author draws the following conclusions as regards the behaviour of the two materials under the various types of corrosion.

(a) *Atmospheric Corrosion.*—The copper steel is rather less corroded than the ordinary steel, but especially so in the more corrosive industrial atmosphere at Attercliffe. This applies to both material with rolling scale on and with the same removed. Material with the scale removed is more resistant than with the scale on, confirming what is generally found to be the case.

(b) *Sea-Water.*—The ordinary steel corrodes the more rapidly at first;

Table II.—Comparative Corrosion Tests of Mild Steel with and without Addition of Copper.

Specimens 0·06″ × 6″ × 3″ supplied by Mr. D. M. Buck. Area 240 sq. cm.

Analysis.	C.	Si.	S.	P.	Mn.	Cu.
A1–8	0·12	0·008	0·037	0·023	0·53	0·268
B1–8	0·14	0·007	0·038	0·023	0·53	0·018

Specimen No.		First exposure.			Second exposure.		
		Period.	Loss in mgrms. per sq. cm.	Relative loss. Mild steel = 100.	Period.	Total loss in both periods. Mgrms. per sq. cm. of original surface.	Relative loss. Mild steel = 100.
Atmospheric at Hathersage.							
A 1	R.	3 months	7·1	90			
B 1	R.	3 „	7·87	100			
A 1	S.	3 „	9·13	75			
B 1	S.	3 „	12·10	100			
Atmospheric at Attercliffe.							
A 2	R.	3 months	18·40	75			
B 2	R.	3 „	24·70	100			
A 4	S.	3 „	22·40	77			
B 4	S.	3 „	29·00	100			
Artificial Sea Water. A 3·1 per cent. solution of Tidman's Sea Salt in Sheffield Tap Water.							
A 3	R.	21 days	1·33	69	3 months	6·38	91
B 3	R.	21 „	1·93	100	3 „	7·00	100
A 6	S.	21 „	1·43	64	3 „	7·57	97
B 6	S.	21 „	2·22	100	3 „	7·77	100
Coal Tap Water (Sheffield).							
A 7	S.	21 days	1·33	72	3 months	9·30	101
B 7	S.	21 „	1·85	100	3 „	9·16	100
50 per cent. Sulphuric Acid in Sheffield Tap Water.							
*A 3	R.	7 days	1·73				
A 8	S.	21 „	32·90	70	3 months	41·42	13
B 8	S.	21 „	46·80	100	3 „	315·80	100
20 per cent. Sulphuric Acid in Sheffield Tap Water.							
*A 8	R.	7 days	24·3	8			
*B 3	R.	7 „	309·0	100			

For the second exposure period the specimen was in the condition as left after the loose corrosion products from the first test had been removed for weighing.

R. indicates rolling scale removed initially and surface polished.

S. indicates rolling scale on the specimen.

* Indicates specimen had been used for an earlier test, corroded surface removed then repolished.

The volume of corroding medium in the laboratory tests was 1 litre.

In the case of the exposures for 3 months in artificial sea water and tap water, the liquid was changed every 14 days, the loose rust being washed off in running water before re-immersion.

In the case of the exposures for 3 months in 50 per cent. sulphuric acid, the liquid remained unchanged throughout the period.

subsequently the rate of corrosion for both materials slows up, indicating a certain degree of "self-protective" action, which is rather more pronounced for the ordinary steel. This is best seen in fig. 1. At the end of 16 weeks, however, the total extent of the corrosion of the copper steel is still less than that of the ordinary steel. The relative behaviour of the material with scale on and that with the scale removed is the same as for atmospheric corrosion.

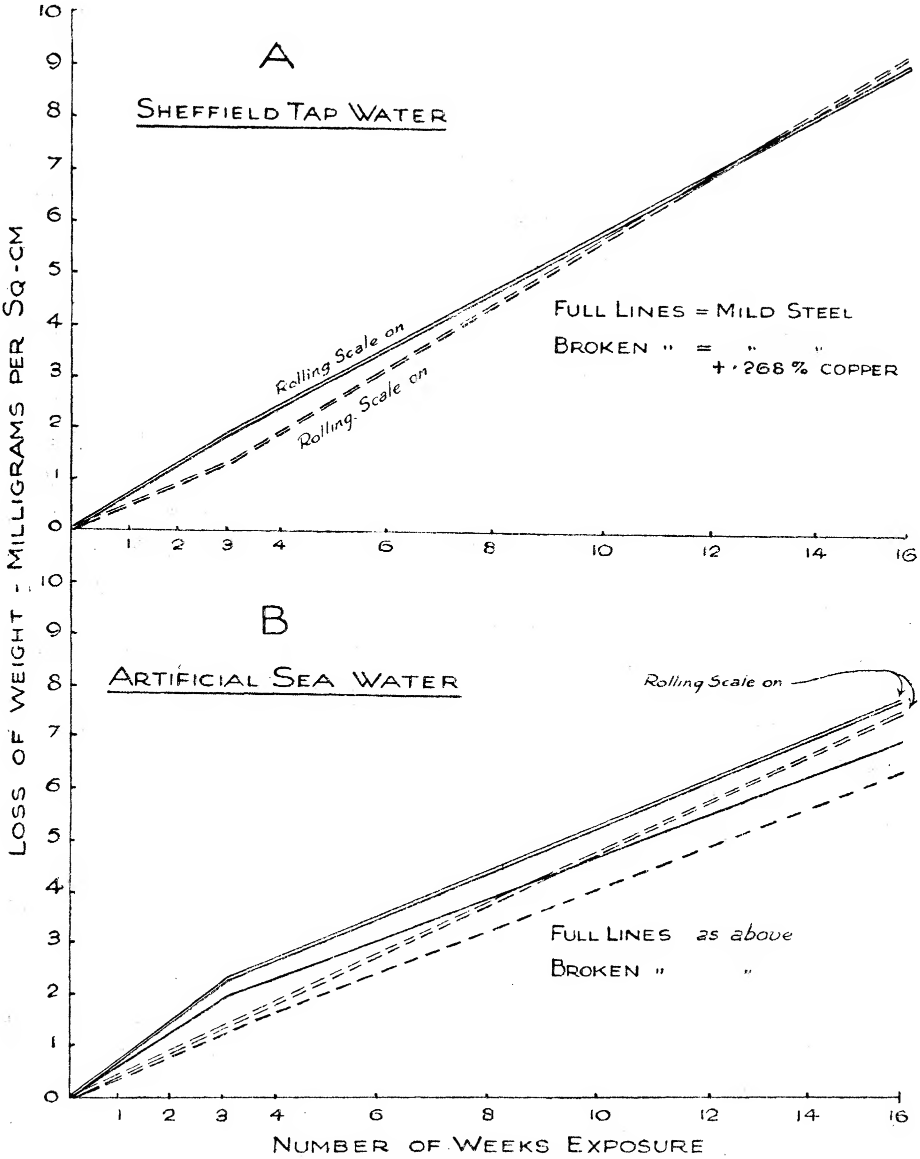

Fig. 1.—Tap and Sea Water.

(c) *Tap Water.*—There is little to choose between the two materials, which maintain a fairly constant rate of corrosion over nearly 4 months. The tap water, which initially is not so corrosive as sea-water, over the longer period is more corrosive, due to the absence of self-protective action of the steels against this medium. In this case no specimens were tested with their rolling scale on.

(d) 50 *per cent. Sulphuric Acid.*—With the original scale on, both materials were attacked very rapidly at first; while, however, the rate is maintained subsequently for the ordinary steel, that is solution goes on at a steady rate, when re-immersed after a 3 weeks' exposure and weighing, the steel containing copper is only very slowly attacked. During the 3 months' period of the second immersion the rate of corrosion is only about one-sixteenth of the rate during the first period of 3 weeks. Apparently, therefore, when the scale has become detached and the attack takes place more directly on the surface of the steel, the steel containing copper is very resistant to a 50 per cent. solution of sulphuric acid. That this is so was confirmed by a 7 days' test on a freshly prepared and polished specimen free from scale (see fig. 2).

(e) 20 *per cent. Sulphuric Acid.*—A seven days' test on specimens with the scale removed, while showing more vigorous action than the 50 per cent. solution, confirms the great superiority of the steel containing copper against attack by sulphuric acid (see fig. 2).

In the author's tests, therefore, the conclusions arrived at, both from the American and the German tests, as to the superior resistance of mild steel containing a small percentage of copper to atmospheric corrosion, are borne out, not however to the extent shown by the American tests. The superiority amounts to about 10 per cent. in pure air, increasing to about 25 per cent. in an industrial atmosphere.

As in the German tests, the results of immersion in sulphuric acid point strongly to this superiority under atmospheric corrosion being due to and dependent on the amount of sulphurous impurity carried by the air.

The author's tests, so far as immersion in ordinary water is concerned, confirm Dr. Cushman's opinions, and also the German conclusions, that is, no advantage for the copper steel is to be looked for in this direction. In sea water the above tests indicate, at any rate for a comparatively short period of exposure (a few months), a certain superiority for the copper steel. With a very long period of exposure, however, it is possible this superiority may be wiped out, or even negatived, and in this respect again they bear out Dr. Cushman and the German conclusions.

It has been suggested that the very outstanding results obtained in America for the copper steels were to some extent due to the superior physical condition of the steel as compared with the ordinary mild steel. A pair of tested specimens received from Mr. Buck through Dr. Friend

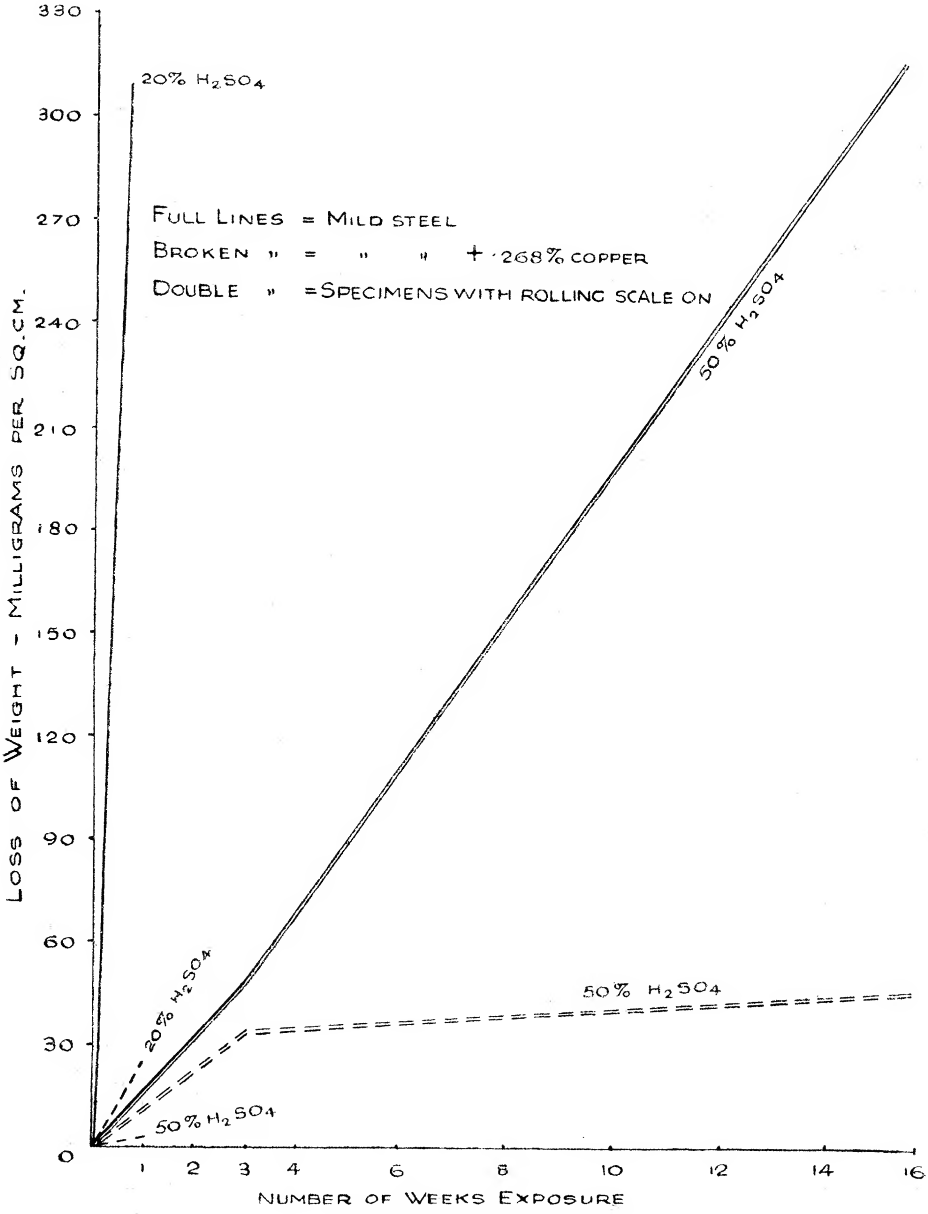

FIG. 2.—Sulphuric Acid.

gives some support to this idea. These specimens, of corrugated sheeting, have been exposed for twenty-three months to the atmosphere at Atlantic

City, U.S.A.; the copper steel was very little corroded, while the ordinary steel had become very thin, with a number of holes corroded completely through the sheet, the surface otherwise badly pitted. The latter, on examination, showed a particle of scale at the bottom of each pit, forming a centre for corrosion, and it was evident that in rolling the material had been very much oxidised and the scale rolled deeply into the sheets. The scale from the copper steel sheet had been completely corroded off in an even manner, and left no pockets containing scale, a circumstance of undoubtedly favourable influence in determining the subsequent behaviour of the sheet.

The specimens on which the above series of tests were carried out by the author do not show any marked difference in the nature or amount of the scale as between the two materials. Micrographic examination, however, showed a difference in structure between the materials, that is, as received and as tested above. While both materials showed the usual character of mild steel, that is, mainly ferrite grains with carbon distributed in the form of carbide of iron; in the case of the steel containing copper, the carbide is invariably confined to the grain junctions; in the mild steel, on the other hand, the carbide is indiscriminately distributed throughout the material. In these circumstances it was not possible to attribute the superior qualities of the copper steel definitely to the presence of copper *per se*, since it is known that physical condition in general has a distinct influence on corrosion.

In order to investigate this point further, therefore, the author carried out the following tests:—

Pieces cut from specimens A1 and B1 (previously tested under atmospheric corrosion) were heated together to 800° C. and cooled in air. This had the effect of normalising both materials, and their micro-structures were then identical, the carbide, in the form of pearlite, being evenly distributed.

After the surface had been removed to a sufficient depth to take away the scale produced by heat treatment and the effects of the previous corrosion tests, and the specimens polished, they were submitted to a further test for twenty-one days in 50 per cent. sulphuric acid, as shown in Table III.

The result shows that even under these more comparable conditions the copper steel is by far the more resistant against attack by sulphuric acid. The relative rates of corrosion are as nine to one. Further specimens tested on the same lines, but heat-treated at 900° C. instead of 800° C., gave full confirmation. The author's experiments, therefore, show that even so small an amount of copper in mild steel as 0·25 per cent., or only 1 part in 400, can exert a very marked inhibiting influence against corrosion by sulphuric acid, and against atmospheric corrosion, in so far as the latter is due to sulphurous impurities in the air. What precisely is the manner in which the copper effects this improvement is at present little understood and difficult to investigate. Further work is, however, being undertaken in order to obtain information if possible on this point.

Table III.—Corrosion Tests on Specimens of Mild Steel, with and without Additions of Copper, in Similar Physical Condition.

The materials are the same as those referred to in Table II.
Specimens immersed in 50 per cent. sulphuric acid, by volume, for 21 days.
Size of specimens 0·15 × 7·6 × 2·5 cm. Area 40 sq. cm.

Analysis.	C.	Si.	S.	P.	Mn.	Cu.
A1	0·12	0·008	0·037	0·023	0·53	0·268
B1	0·14	0·007	0·038	0·023	0·53	0·018

Rolling scale removed and specimens polished.

Specimen No.	Heat treatment.	Loss in mgrms. per sq. cm.	Relative loss. Mild steel = 100.
A1	Heated to 800° C. and cooled in air	4·8	11
B1	Heated to 800° C. and cooled in air	43·8	100
A1	Heated to 900° C. and cooled in air	4·2	8·4
B1	Heated to 900° C. and cooled in air	50·2	100

Conclusion.

It seems wise to include a few words of caution in regard to forming general conclusions as to whether a small percentage of copper as a constituent of steel is really desirable for general service conditions. As shown in this paper, a small copper-content, say 0·16 to 0·25 per cent., is beneficial, provided the condition is that of *bare* metal exposed to atmospheric corrosion, especially in a sulphurous atmosphere. But no recorded tests have yet shown that *coated* metal would be benefited by a copper-content. Some investigators have held that, so far as galvanised metal is concerned, the purer the base metal or the freer it is from impurities the longer life will be obtained in average service.

Unquestionably, in the majority of service conditions, iron or steel is subjected to either total or partial immersion in natural waters, or some sort of liquid phase. It is by no means certain yet that, under such conditions, a copper-content in steel might not actually be deleterious, and it is fair to state that this opinion is held very strongly by Dr. Cushman and other investigators who have been long studying these problems. The study is exceedingly difficult, owing to the fact that a given type of iron or steel, which may behave very well under one set of conditions, will quite reverse its behaviour under another set. It is necessary, therefore, to proceed with extreme care before drawing important conclusions on the basis of any tests so far carried out, which might be the means of inducing steel manufacturers generally to introduce copper as a commercial constituent of mild steels.

It should be noted that if such a practice came into general use, the scrap of the steel manufacturing countries would become greatly infected with copper, which is not thereafter removable by the various refining processes now employed. If future experience should tend to show that a copper-content was in many cases deleterious rather than beneficial, this would be a most serious and important consideration.

In this paper the author has not considered the question of the high chromium-steel alloys containing about 12 per cent. of chromium and from 0·10 to 0·60 per cent. of carbon, known under the names of "rustless," "stainless," and "non-corrosive." Such material is very expensive, and does not immediately concern the ordinary user of iron and steel in large quantities. If these experiments help to show how it is possible to obtain steel as little subject to corrosion and lower in cost than the type just mentioned, they will have served a useful purpose, as well as drawing the attention of our Society to this important subject.

In these various researches, carried out at Hecla Works, Sheffield, the author has had the assistance freely rendered of Mr. I. B. Milne, B.Met., and Mr. W. J. Dawson; also Mr. T. G. Elliot, F.I.C., as regards analytical and micro-examination and the corrosion tests; Mr. S. A. Main, F.Inst.P., has given general supervision and arranged the specimens. The author takes this opportunity of expressing his best thanks to those who have rendered valuable assistance in this research.